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A systematic review of consequential LCA on buildings: the perspectives and challenges of applications and inventory modelling

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Abstract

Purpose. The built environment has demonstrated the limited nature of applications of consequential LCA (LCA), whereas attributional LCA (ALCA) is applied in most situations. Therefore, this study aims to clarify the contexts in which CLCA might be applied and the state of CLCA on buildings by examining the following research questions: (i) How are the goal, scope and methodological aspects and associated gaps of CLCA of buildings addressed in the literature? (ii) How can these insights guide the applications of CLCA on buildings?

Methods. The study employed the Systematic Literature Review methodology, which yielded 37 relevant studies. The study examined the sample regarding intended applications, the contexts of micro or meso/macro decision-making support, and the consequential life-cycle inventory modelling (CLCI) of time horizons, market delimitations, market volume trends, affected suppliers, constrained supplies and substitution. Furthermore, the basis for choosing either an ALCA or a CLCA approach was evaluated based on the ILCD Handbook.

Results and discussion. Many studies include an empirical assessment, yet with half of those combining it with an evaluation of selected methodological aspects, CLCA on buildings seems to still be in the earlier exploration phase. In general, the empirical CLCAs emphasize the decision-making aspect in the stated application of the study. Furthermore, CLCA studies show an almost equal distribution of focus between the micro and meso/macro levels of decision support. This entails that CLCA on buildings currently applies to both material- and building-level assessments and policy situations. The inclusion of CLCI modelling elements varies: e.g., nine studies only include substitution as the single CLCI element. Additionally, modelling methods are described at various levels of detail, and with critical differences in the transparency of documentation. This, therefore, suggests that the consistency of included CLCI elements is inadequate, as is how they should be modelled.

Conclusions and recommendations. Building on the ILCD Handbook, this study presents a proposal for deciding when to select CLCA on buildings. This is a proposal for a simple and clear distinction threshold between the micro and meso/macro levels. Additionally, CLCA on buildings need a more harmonized approach to CLCI modelling to increase and improve, which the built environment community could achieve by settling on a standard for the inclusion of CLCI elements and associated modelling methods.

Keywords. Consequential LCA, consequential modelling, decision support, building, built environment, construction sector, review.

1. Introduction

Buildings contribute extensively to global energy use, resource consumption and greenhouse gas (GHG) emissions causing global warming (United Nations Environment Programme, 2021). Therefore, mitigation of GHG emissions has been a crucial focus in the broad ratification of the Paris Agreement, whose goal is to stay well below a temperature increase of 2 degrees Celsius and preferably under 1.5 degrees Celsius (United Nations, 2015).

This goal stimulated the development of EU policies regarding the decarbonization of buildings. More recently, the Green Deal launched its goals towards 2050, and legislation on particularly energy use and renovation strategies has attracted notice (EU, 2010; EED, 2012; European Commission, 2020). The major challenge of decarbonization of buildings has created a shift to targeting the embodied carbon of buildings as well because the reduction in embodied emissions is lacking behind the improvements for emission reductions in the operational phase (Hoxha *et al.*, 2017; Röck *et al.*, 2020). Furthermore, Denmark, the Netherlands and France have introduced requirements of national GHG emissions regulation for buildings in a life-cycle perspective, with more legislative initiatives in preparation internationally (Toth *et al.*, 2021).

Often, assessments of environmental impacts and resource use associated with buildings include a life-cycle assessment (LCA). LCA quantifies the exchanges with the environments from raw material extraction and production to operations and end of life, and allows for identifying the impacts and burden-shifting between stages of the life-cycle (Finnveden *et al.*, 2009). LCA has its own international standards (ISO 14040 and 14044), and a more detailed consensus guideline in the ILCD Handbook (JRC-IEA, 2010). Additionally, there are specific standards for the application area of buildings (EN 15978 and EN 15804),

LCA has two overall approaches: attributional LCA (ALCA) and consequential LCA (CLCA), according to the ILCD Handbook (2010). They are often associated with the ability to answer different questions. Hence, the defined purpose and related questions determine the appropriate approach (Gustavsson *et al.*, 2015). ALCA can answer questions related to a supply chain's optimisation potential or evaluate a specified system's impact. CLCA can answer questions regarding the impacts of imposing a change on a system or the effect of increasing the demand for a certain product or service.

Building LCAs mostly apply the attributional approach (Khasreen *et al.*, 2009; Buyle *et al.*, 2013; Anand and Amor, 2017; Nwodo and Anumba, 2019; Sauer and Calmon, 2020; Fauzi *et al.*, 2021), thus leaving application of building CLCA in its fairly early stages (Buyle *et al.*, 2013; Röck *et al.*, 2020; Saade *et al.*, 2020). Consequently, attributional-based conclusions shape most environmental and climate policy decisions on buildings. The ALCA-based decision-making might overlook aspects identified by the consequential approach since the latter considers the processes in the system that are affected by a change induced in the economy. The attributional approach generally does not include these indirect dynamics. A study of a Belgian dwelling found that the impact from water during the use phase was 57% higher for CLCA than for ALCA because the unconstrained treatment technologies (modelled in CLCA) had a higher impact than the average market treatment technology (modelled in ALCA) (Buyle *et al.*, 2018a). Also, it is debated whether CLCA can better inform certain policy decisions regarding GHG mitigation(Brandão *et al.*, 2014; Plevin *et al.*, 2014). Therefore, the CLCA of buildings needs more attention if it is to have a role in and provide perspectives for the sustainable transition of buildings.

1.1 LCA and consequential framework

This section explains ALCA and CLCA as described in the ILCD Handbook (2010), including acknowledgement of internal incoherencies, and a description of the frequently applied methodological framework for CLCA."

The ILCD Handbook (2010) describes ALCA as an "actual or forecasted specific or average supply-chain plus its use and end-of-life value chain.", and CLCA as a "generic supply-chain as it is theoretically expected in consequence of the analysed decision." The chapters on the definition of goals and scope in the ILCD Handbook show when to apply which LCA approach. This is termed the decision context, which distinguishes whether the LCA will be used as support in decision-making or not. When the goal and scope of an LCA involve decision-making support, either Situation A (micro level) or Situation B (meso/macro level) is concerned, otherwise Situation C (accounting) is involved, according to Chapter 5, 'Goal definition', in the ILCD Handbook. The first two decision-making contexts or situations lean conceptually more towards CLCA with statements such as "the extent of changes that the decision implies in the background system and other systems and that are caused via market mechanisms." Moreover, "whether a decision is to be supported implies whether the study is interested in the potential consequences of this decision." The consequential direction follows for micro level studies i.e., "cases with only small-scale, non-structural consequences in the background system", and for meso/macro level studies "cases that have large-scale, structural effects".

When the ILCD Handbook advises on life-cycle inventory (LCI) in Chapter 6.5, it depicts attributional modelling as appropriate for micro level and accounting studies. However, the same applies to meso/macro level studies, with the modification that "processes that have been identified as being affected by 'big' large-scale changes as consequence of the analysed decision shall be modelled as the market mix of the long-term marginal processes". This implies some consequential LCI (CLCI) modelling. Overall, this evokes some ambiguity between the goal and scope chapters and the chapter on LCI modelling, also concluded by Ekvall et al. (2016). This article interprets Situations A and B as consequential because the ILCD Handbook leans towards consequential descriptions of these. Therefore, the goal and scope determine when it is a CLCA, while the scale (Situation A or B) influences the CLCI modelling. The remaining part of the CLCA approach is analysed against the framework of Weidema et al. (2009) due to the incoherence between goal and scope and the relevant LCI modelling in the ILCD Handbook.

The CLCA framework has evolved since the early 1990s (Weidema, 1993, 2003; Weidema *et al.*, 1999, 2009; Ekvall and Weidema, 2004), complemented by, for instance, theories of multifunctionality and system expansion (Ekvall, 2000; Weidema, 2001). The CLCA framework encompasses the market mechanisms of effects due to changes in demand, all other demands remaining constant, i.e., the ceteris paribus assumption (Zamagni *et al.*, 2012). Despite the framework, CLCA lacks a harmonized CLCI modelling method both in general (Earles and Halog, 2011; Zamagni *et al.*, 2012) and for buildings (Almeida *et al.*, 2020).

A few reviews exist on the application of CLCA in general, although none about the specific application area of construction. Zamagni et al. (2012) conduct a goal and scope review of general CLCA and of when to use CLCA, although a detailed analysis of CLCI modelling was beyond the scope of the study. Earles and Halog (2011) and Almeida et al. (2020) review economic models used in CLCI both in general and for buildings but refrain from studying all aspects of the CLCI according to the stepwise procedures (Weidema, 2003; Weidema *et al.*, 2009) and the goal and scope aspects of the reviewed studies. Therefore, knowledge is needed about where building CLCAs currently stand in the focus between developments in CLCI modelling development, method analysis and empirical studies, as well as the level of decision-making support they inform. This is followed by understanding the coverage and disclosure of CLCI aspects to grasp where harmonization is needed.

This study therefore aims at combined coverage of the goals and scope of CLCA on buildings and applied CLCI aspects in relation to the four-step procedure of Weidema et al. (2009) by conducting a systematic literature review. These insights will aid awareness of where the focus of building CLCAs lies between analytical and empirical studies, and the focus and level of decision support alongside the comprehensiveness of CLCI modelling. This should ultimately lead to holistic recommendations for CLCA practice in the built environment. Thus, this study investigates the following research questions:

- How is CLCA on buildings addressed in the literature, in terms of the goal, scope and methodological aspects?
- What are the prevailing gaps in CLCA approaches and methodology used for environmental assessments of buildings on the micro and meso/macro levels as defined by the ILCD Handbook?
- How can these insights guide the application of CLCA on buildings to increase implementation where it is appropriate?

2. Methodology

The methodology describes the systematic literature review process and the execution of data and information extraction from the identified studies based on the ILCD Handbook and Weidema et al. (2009).

2.1 Systematic collection of literature

This study used a systematic literature review to obtain a comprehensive collection of the relevant literature. The review followed the structure of a search protocol and a stepwise systematic approach to achieve transparency and documentation based on the systematic research ontology provided by de Almeida Biolchini et al. (2007). This approach to the literature review will cover most of the studies relevant for mapping and analysing CLCA studies on buildings.

We formed a search protocol of the relevant keywords and their synonyms to aid in searches in the chosen search databases. Keywords encompassed four main subjects associated with the research questions and were separated into four blocks: consequences, environmental assessment, approach, and building-related (see Table 1 in Supplementary Material). The inclusion criteria for studies were a publication date from January 2000 to 14th September 2021, both months included. We considered all English-language journal articles and conference articles, as well as grey literature in Danish, Swedish and Norwegian due to the authors' ability to read these languages. Two criteria were used as a filter in evaluating the literature, both having to be satisfied to ensure we collected the desired articles.

1. The study must include a consequential LCA case study of a building, a building component or a building material that is defined as consequential in the article itself.
2. The study must provide sufficient information on applied methodological choices e.g., inventory modelling, multi-functionality handling and studied consequences.

Scopus, Web of Science and Google Scholar were chosen as relevant search databases. All retrieved studies were filtered by looking at the title, abstract and keywords to include only relevant articles. All selected studies were then read to confirm their relevance. This resulted in a total of 35 relevant studies. A bibliographic check of the reference list and citations of the 35 studies was performed (Wohlin, 2014), which yielded two additional relevant studies.(see Fig. 1).

2.2 Data extraction

The information about goal, intended application, and questions addressed was extracted from the descriptions in the reviewed studies. Intended applications and addressed questions cover each study's definition of their aim, purpose, goal, or objective, which can include one or more intended applications for each study.

Next, the reviewed studies were categorized into four, depending on their intended application. The categories were 1) method development and case testing, 2) method analysis, 3) method and empirical analysis, and 4) empirical analysis. 'Empirical' connotes that a study includes a case study examination. Studies were added to the category 1) of method development and case testing when the study proposed a new method to model one or more aspects of the CLCI, such as market delimitation, market trend and affected suppliers. The studies test their methodological developments of the part of the CLCI that their methods were developed for in a case study. However, they refrain from conducting a CLCA involving the definition of goal and scope, thus they are not included in the 28 studies that are categorized as empirical analysis. Category 2) of the methodological analysis consists of studies scrutinizing CLCA and the influence of general LCA methodological aspects on the CLCA outcome but where no empirical-based intended application was stated. Category 3) of the studies of methodology and empirical analysis covered methodological analysis and an empirical assessment. The methodological analysis comprises both CLCA and general LCA characteristics. Ultimately, category 4) of the empirical analysis was confined to studies examining cases whether the intended application was consequentially or non-consequentially formulated, but where the authors state they conducted a CLCA. For categories 1) to 3) involving method analysis, we derived a characterization of the focus of each study, which could involve one or more focuses per study, depending on the intended applications. The characterization of the method focus could be general LCA aspects, e.g., end of life, temporal aspects, ALCA and CLCA impact comparison, or consequentially focused, e.g., retro- and prospective data comparison, or the size of the delimited market.

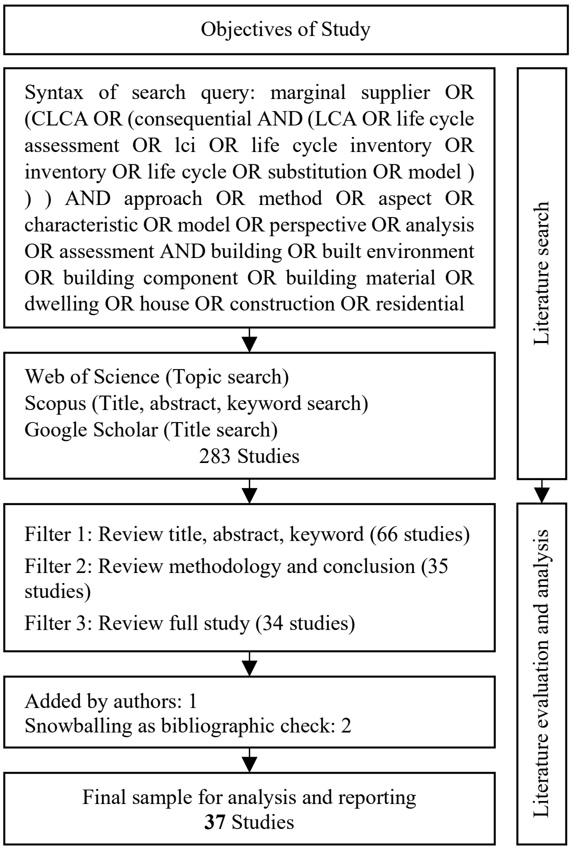

Fig. 1 Methodology of searching for and analysis of relevant studies including results of number of studies. The query was modified to suit rules of each of the three search databases

2.2.1 Characterization of decision context

The ILCD Handbook describes how an LCA for decision support belongs to the situations of either the micro or meso/macro levels, which defines the scale of the study. Even though the ILCD Handbook depicts attributional modelling for the micro level and more consequential modelling for the meso/macro level, the reviewed empirical studies of CLCA were still grouped into these two decision contexts because they did not necessarily base their choice on the ILCD Handbook. Studies of methodological development or of methodological aspects of (C)LCA were not considered relevant for the grouping of decision contexts. It is because they use case studies with the goal not of drawing conclusions about the consequences of change induced by the case study, but of understanding how the methodological aspects influence the CLCA outcome.

Table 1. Characterization of decision contexts for the grouping of empirical studies. Adapted from the ILCD Handbook

Decision Context	*Criteria*	*Grouping Focus*	*Focus Description*
Micro level	Not mediating decision support for policy	Material comparison	Comparison of materials, material constituents, or material processes
		Design strategy	Strategies for energy, structural design, circularity, or material use
Meso/macro level	Mediating decision support for policy	Policy information	Comparison of options to reach a policy goal
		Policy development	Comprehend consequences that a particular policy choice imposes

The criteria for grouping studies into the two decision contexts are presented in Table 1. Examples of meso/macro level grouping for purposes of policy information could be the choice of renewable energy expansion or increased insulation for climate impact reductions of buildings. For policy development it could be the consequences of increasing the demand for wood for residential buildings. Each study was assigned an object of study as either material, component or building. Studies analysing a building structure were also reported as a building object. Subsequently, the empirical studies were grouped by their decision support on either the meso/macro or micro levels.

2.2.2 CLCI modelling information

The collection of CLCI modelling information was based on the framework of Weidema et al. (2009). It included the time horizon, market delimitation, market volume trend, affected suppliers, constraints and multifunctionality handled by substitution. In the framework, the scale element was considered identical to the decision support level where small-scale equals micro level and large-scale equals meso/macro level. The time horizon was collected if the studies explicitly defined it as short-, medium-, or long-term, or had a defined reference period as in the ILCD Handbook. Here 0-5 years equal short-term, 5-10 years equal medium-term and more than 10 years equal long-term. Market delimitation, market volume trend, and affected suppliers were analysed, if disclosed, regarding the methods of modelling or identification used in each study. Furthermore, the level of specification i.e., the level of documented detail, of this CLCI modelling was evaluated for each study at three levels: low, medium, or high, provided the respective study included the CLCI aspect (for detailed information, see Table 4 in the Supplementary Material). A low specification level specifies a CLCI aspect but omits the elaboration of modelling and choices, e.g., by applying an ecoinvent consequential database but overlooking considerations of processes and location effects (Prateep Na Talang *et al.*, 2017). A high level is shown by describing and displaying the formulas, thresholds and considerations of identifying the market (Buyle *et al.*, 2018b). The medium level is often a high-level specification of some aspects and a low level of the remaining.

3. Results

First, the results of the intended applications are aggregated into four focus areas where the intended applications, including the methodological aspects, are further disaggregated and arranged according to their focus. Subsequently, studies are organized around their decision support at the micro or meso/macro level, including a description of changes and of the object of assessment. The section finally analyses the applied time horizon and CLCI methodological aspects.

3.1 Intended applications of CLCA studies

The intended applications of an LCA study set the scene for one or more purposes of the study, which will define the LCA approach according to the ILCD Handbook. The intended applications and formulated questions lead to selections of whether a study focuses on methodological development and case testing, methodological analysis, empirical assessment, or a combination, and what is the aim of interpreting the results of the LCA conduction. For a study to be consequential, the intended applications should include at least one formulation with the principle of the consequence of a decision. See e.g., Table 2 in the Supplementary Material for the division of the intended applications of each study into non-consequential and consequential.

The focus of the intended applications in Fig. 2(a) reveals that most studies, 27, aim at examining an empirical consequence. Half of these studies also analyse the general methodological aspects of LCA, such as the end of life, or ALCA and CLCA icombined with the empirical assessment of the case study. In total, ten studies focus on the non-empirically consequential aspects. These studies can be consequential but understood as having the purpose of solely examining CLCA method-related aspects. It could be comparing the ALCA and CLCA of a particular case, criteria for the inclusion of affected suppliers, or purely studies of methodological development for CLCI modelling.

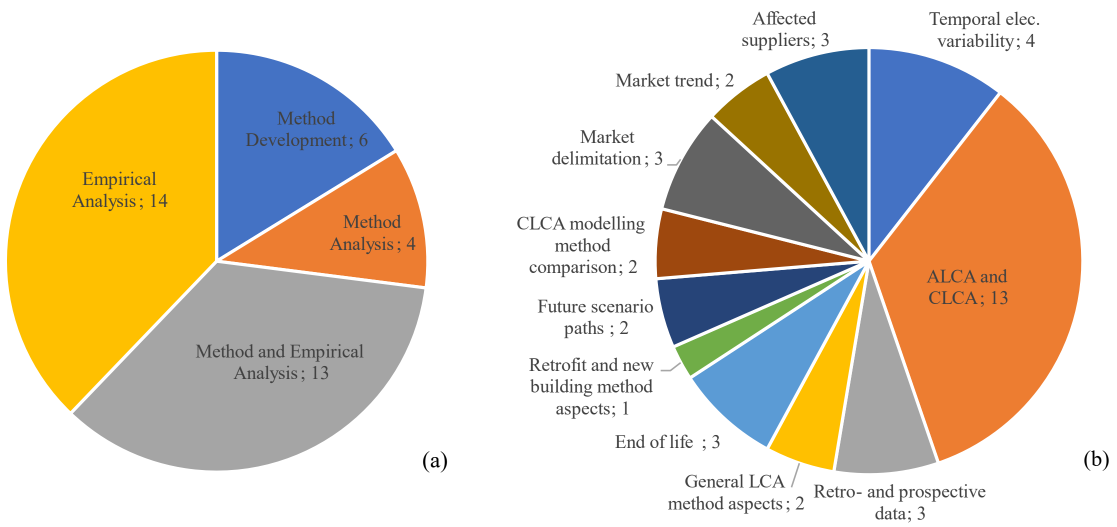

Fig. 2 (a) Reviewed studies separated into four aggregated focus areas of intended application and formulated questions i.e., method development and empirical test, method analysis, method and empirical analysis, and empirical analysis. (b) Show the methodological aspects represented as the number of times they are applied across the reviewed studies. Methodological aspects cover both CLCA and general LCA aspects that are examined in the studies regarding the impact on the CLCA. (The focus of the 28 studies with empirical assessment is elaborated in section 3.2)

In this review, empirically intended applications involving decisions converge mainly on (i) comparing options of materials, structural configuration, or production processes; (ii) increases of a certain material, component, or building type; (iii) breakthrough of a technology; (iv) substitution of one material for another; (v) choice of increased circular demand; and (vi) growth of retrofitting. The concept of studying a consequence of a decision, could in the intended application be explicitly written as "What are the environmental consequences of constructing more hybrid wood multi-storey buildings in 10 years?" (Fauzi *et al.*, 2021). In several of the reviewed articles, this emerges more as an implied part of the intended application, such as "Compare the environmental impact of RC structures and timber structures" (Skullestad *et al.*, 2016) or "What are the potential environmental impacts of an increase in resource demand associated with energy efficiency refurbishments?" (Ghose *et al.*, 2017). The substance of these intended applications and questions is that they circle around a decision that changes the status quo. This shows that CLCA could be applied to studies that include those sets of purposes.

Representation of the methodological aspects across the studies displayed in Fig. 2(b) is widespread (Table 3 in the Supplementary Material shows the representation for each study). Nonetheless, comparison of ALCA and CLCA appears to be the main methodological focus, examined in thirteen studies. Temporal electricity (elec.) variability, end of life, and retro- and prospective data comparison follow. Among the studies of methodological development most articles consider market delimitation and affected suppliers. The two studies comparing future scenarios analyse the influence of three trajectories of global warming in buildings' energy consumption and the impact on future dwelling stock of two different electricity mixes.

3.2 Decision support level and the focus of studies

Choosing CLCA as the approach, whether the decision support is at the micro or meso/macro levels plays an essential role in the proceeding approach of the LCA modelling method, and in the interpretation of the outcome and conclusions.

3.2.1 Policy characteristics of meso/macro level decision-making support

Fifteen studies have meso/macro decision support. Two thirds of the studies in Fig. 3 focus on policy development, and only a few on policy information. Studies of policy development address mainly the implications and effects of the environmental impacts of a decision to change the status quo through projected scenarios. One study examines the impact of increased hybrid wood multi-storey residential buildings, avoiding an emphasis on a particular policy, but analysing the consequences if policy would implement a perspective involving increased use of wood (Fauzi *et al.*, 2021). Policy information studies compare various options for obtaining a policy goal. Pedinotti-Castelle et al. (2019) illustrate this by evaluating whether retrofitting the residential sector would improve the environmental and economic impacts more than installing new power plants to replace fossil-fuel energy sources.

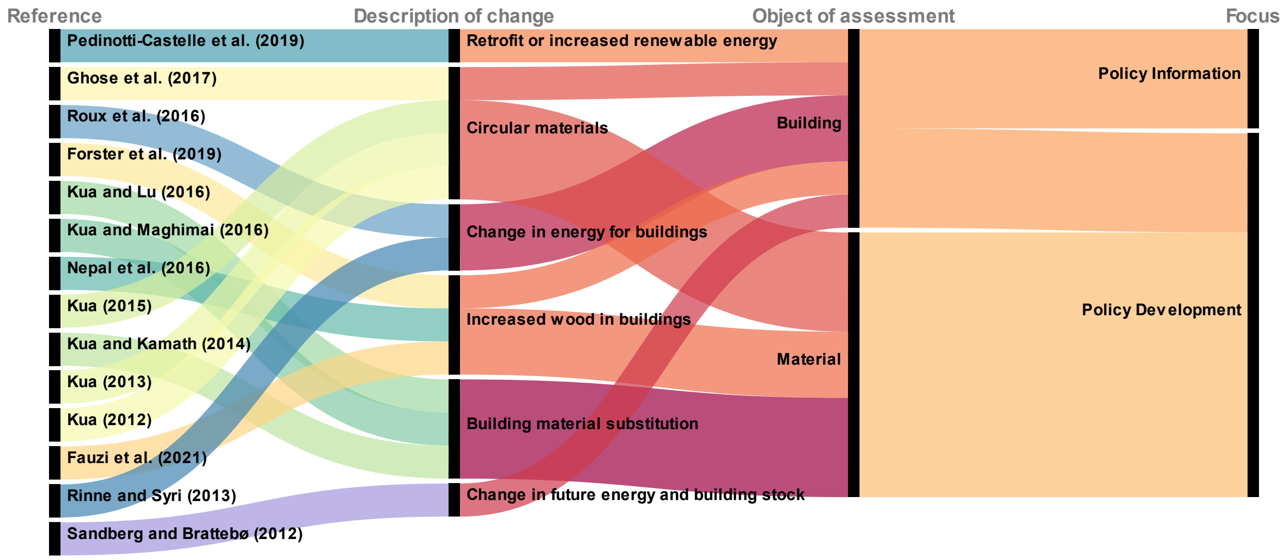

Fig. 3 Network of meso/macro level decision support studies' relation with their focus, object of assessment, and aggregated description of the change under study. It includes only studies that involve an empirical assessment. Policy information is comparison of alternatives to reach a policy goal. Policy development examines the effects of one policy proposal

All four policy information studies have buildings as their assessment target, while the policy development studies are distributed among eight material- and seven building-oriented studies. For policy information regarding buildings, the studied changes converge on circular material options, a choice of retrofitting or constructing new buildings, and changes in energy use for building design assumptions. One case of renovation explores the opportunity to reduce the impacts of increased demand for materials from a refurbishment by analysing strategies of circularity on site and the procurement of greener materials (Ghose *et al.*, 2017). Building as an object in policy development focuses on the consequences of increased construction with wood, the development of energy supplies, and the relation between energy and building stock. The latter is a national-scale study that ascribes existing energy policies and GHG targets. It examines the GHG impact of the energy demand of the future dwelling stock associated with an increased building area due to population growth, and how that demand governs the overall obligation to decarbonize (Sandberg and Brattebø, 2012).

Studies with material as an assessment target focus exclusively on policy development. Six of the eight articles appraise various material strategies in Singapore related to changes in constituent or material substitution and recycling, e.g., concrete production, bricks displacing concrete, and the importance of perusing technology for its short-term processual aspects and long-term policy guidelines for concrete production and the integration of waste products (Kua, 2012, 2015). The remaining two material studies draw consequences for increasing the number of wood products in the building industry. Here, the demand for wood in houses and low-rise non-residential buildings involved cases that explore the net climate-mitigation potential of displacing non-biogenic structural materials with structural wood. They recommend policy-making directed towards structural wood systems due to the reduction potential of climate impacts (Nepal *et al.*, 2016; Forster *et al.*, 2019).

3.2.2 Micro level decision-making support

The thirteen studies of micro level decision support focus on material comparison (8) or design strategy (5) (see Fig. 4). Of the material comparison studies, the majority target solely a material as their object of assessment. Two other studies compare materials, but in the function of a whole building, concentrating on wood displacing conventional structural materials. All the material comparison studies assess the consequences of circularity processes that primarily involve the comparison of waste or by-products, and to a lesser extent forms of energy.

Studies about building design strategies primarily look at the consequences of energy use under different circumstances, or the nexus between the structural and energy design of buildings. For instance, these studies are specifically energy optimization or renovation through energy improvements by means of increased insulation or heat pump installation under various energy-transition scenarios. The choice of structural configuration and energy consumption involves a decision whether energy design or structural design makes the largest contribution to a building's environmental impact. Dodoo et al. (2014) exemplified this in an analysis of three structurally different wood systems of

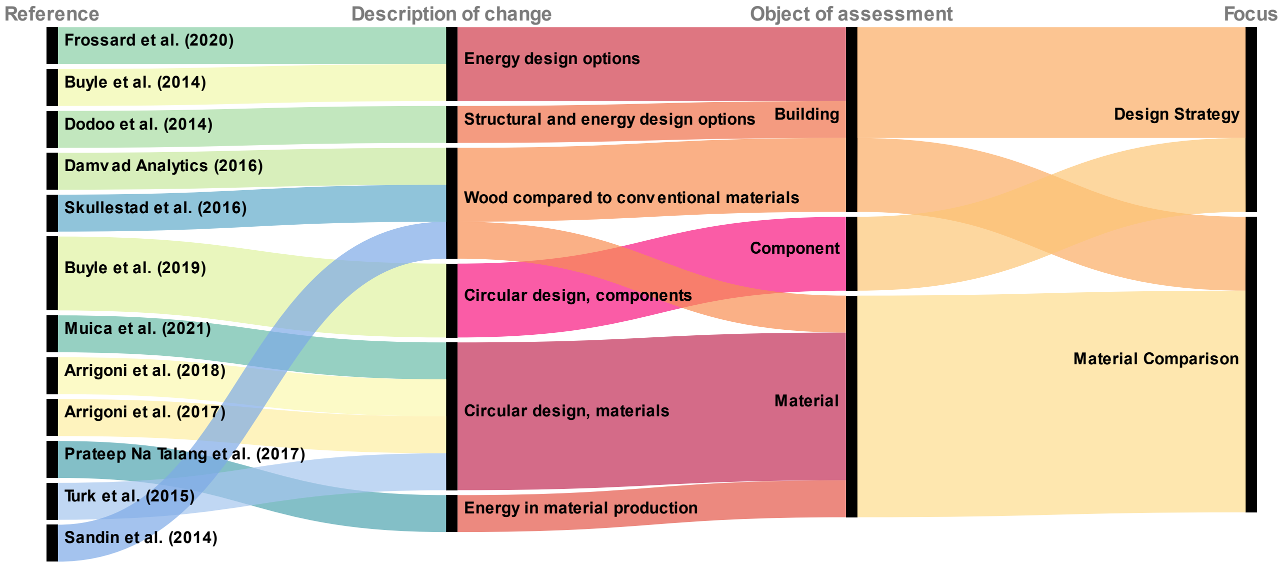

Fig. 4 Network of micro level decision support studies' relation with their focus, object of assessment, and aggregated description of the change under study. It includes only studies that involve an empirical assessment

cross-laminated timber, beam and column, and prefabricated modules designed as conventional and low-energy buildings respectively. The two studies of component design strategies appraise how choices between circular and conventional components affect the environmental impacts of various frequencies in building transformations.

3.3 CLCI methodological aspects

The analysis in Fig. 5 contains an overview of the CLCA aspects, if the reviewed studies include them, and the level of specification, i.e., how well it is described and documented. In an important notice, two of the studies focusing on method development avoid the aspects of time horizon and substitution (Vieira and Horvath, 2008; Pizzol and Scotti, 2017). This is because the purpose of these studies is to develop a method for one or more aspects of the CLCI modelling and to apply that method to that aspect of the CLCI, thus not conducting a full CLCA. Twenty-four studies include a time horizon, mainly practicing a long-term perspective, the default and often the case-study situation stated in Weidema, Ekvall and Heijungs (2009). Two studies combine average and marginal data, and one study only applies average data, which is not included in the theoretical concept. Some analyses adopt short- and/or medium-term time horizons either separately or accompanied by long-term time horizons, which are still within the framework. Overall, the studies encompass three of the pillars of CLCI modelling i.e., market delimitation, 21, market volume trend, 14, and affected suppliers, 26. Yet, each of these has distinct numbers of appearances and a broad spectrum of identification methods (see Fig. 5).

Market volume trends are mostly identified by linear regressions, which align with the linear, steady-state description of Weidema et al. (2009). However, the references to the literature also feature frequently as a method of identification. This is also the case for market delimitation and affected suppliers, ranging from assumptions and ecoinvent as modelling methods to network analysis, iterative procedures, equilibrium models and other market-based models. Most studies include substitution, but the studies without substitution comprise (i) method development studies with only the CLCI modelling as the scope but with the possibility of using the developed method to identify substituted affected suppliers (Vieira and Horvath, 2008; Pizzol and Scotti, 2017; Buyle *et al.*, 2018b; Cordier *et al.*, 2019); and (ii) energy consumption studies with a pre-confined market where substituted suppliers might be inherent in the modelling (Sandberg and Brattebø, 2012; Roux *et al.*, 2016; Frossard *et al.*, 2020).

The method development side comprises different forms of network analysis by identifying affected suppliers and market delimitation top-down from trade and production volumes (Pizzol and Scotti, 2017) and by bottom-up market equilibrium based on retrospective trading volumes (Sacchi, 2017). Otherwise, an electricity system model that captures higher temporal dynamic and marginal aspects of the hourly electricity consumption of a house has been developed (Roux *et al.*, 2017; Collinge *et al.*, 2018). Cordier et al. (2019) assess changes in the supply chains of wood products from increased demand derived from their development of material flow analysis (MFA) for CLCI modelling.

In general, the level of specification of market delimitation, market trend and affected suppliers diverge from low to high, not correlating with how advanced the CLCI modelling is. The inclusion of constraints in modelling or in the discussion section of the reviewed studies emerges as a shifting between high or low levels of specification. The nine studies that only employ substitution as their consequential aspect omit constraints. On the other hand, the studies that only contain substitution have on most occasions the modelling of substitution specified at a high level. (Table 4 in the Supplementary Material presents the detailed modelling method and level of specification for each study).

Eight studies consider both retrospective and prospective data, but with various combinations and purposes. One purpose is an examination of the retrospective and the prospective data of market trends and affected suppliers (Buyle *et al.*, 2018b, 2019b, 2019a). However, in situations with a lack of prospective data, they used retrospective data as proxy data. Another study used retrospective and prospective data as a sensitivity analysis for the electricity mix (Ghose *et al.*, 2017). Moreover, it was examined whether retrospective data for short-term changes and prospective data for long-term changes would yield different conclusions regarding affected suppliers (Rinne and Syri, 2013). An additional application used the retrospective data to extrapolate the prospective data (Sandberg and Brattebø, 2012; Cordier *et al.*, 2019). Finally, one study combines retrospective extrapolate data with prospective economic and biological modelling for increased wood demand (Nepal *et al.*, 2016).

4. Discussion

4.1 Consequential approaches and prevailing gaps

The reviewed studies contain a diverse range of intended applications. Several studies engage with the methodological aspects of either method development, method analysis, or a combination of method and empirical analysis. Many of these studies emphasize the methodological analysis rather than the empirical. Table 2 presents the identified research gaps.

Fig. 5 CLCI aspects of time horizon, modelling methods of market delimitation, market volume trend and affected suppliers as how many times they are represented across reviewed studies. Finally, level of specification is presented for constraints and substitution documentation. Elec. equilib.= electricity equilibrium, PM = power market, PE = partial equilibrium, MFA = material flow analysis

Table 2. Method and empirical gaps in the building CLCA research literature and what those gaps consist of

Study Focus	*Aspect*	*Focus Gap*	*Reference Examples Addressing the Gap*
Method	Market delimitation Market trend Affected suppliers	Examination of the effects of choices in modelling on the final impacts	(Pizzol and Scotti, 2017; Sacchi, 2017; Buyle *et al.*, 2018b, 2019a, 2019b)
Method	Electricity modelling	Combined marginal electricity development and global warming paths	(Roux *et al.*, 2017)
Method	Renovation	Sensitivity to CLCI modelling choices	
Method	Biogenic carbon	Biogenic carbon modelling in CLCA of biogenic products	(De Rosa *et al.*, 2018)
Empirical	Object of assessment	CLCA on building component level	
Empirical	Meso/macro level	Renovation policy and circular economy strategies	
Empirical	Micro and meso/macro level	Material strategies and optimal design of building typology and configuration	

In this review, the meso/macro level decision support would be the focus when studies are projected or coupled to policy-making, since this leads to large-scale changes. When the output of a study remains case-specific without involving policy, it was characterized as micro level, which results in smaller scale changes i.e., marginal changes, within the economy's existing capacity. One limitation is that this review does not consider whether studies involving meso/macro level decision support base their analysis on marginal changes, and hence if they exclude large-scale changes.

4.2 CLCI methodological aspects and limitations

There is a wide range of applied methods in CLCI modelling in the reviewed studies, from simple to sophisticated, while exhibiting different levels in the transparency of documentation. Table 3 lists the identified modelling methods, the covered CLCI aspects and limitations alongside the decision support level they are recommended for. Commonly, it is important to be conscious about removing constrained suppliers due to, e.g., policies, quotas, or resource availability. One limitation of the reviewed studies is the employment of retrospective data for defining constrained suppliers, which might not reflect resource shortages or policies in general.

Table 3. CLCI modelling methods, aspects they cover, limitations, and recommendations for the relevant decision support level

CLCI Method	*CLCI Aspect*	*Limitations*	*Decision Support*	*Reference Examples*
Ecoinvent	Market delimitation Affected suppliers	Market aggregation or lack of representativeness	Micro level	(Prateep Na Talang *et al.*, 2017; Fauzi *et al.*, 2021)
Literature	Market delimitation Affected suppliers	The geographical location needs to be very similar	Micro level	(Buyle *et al.*, 2018a; Pedinotti-Castelle *et al.*, 2019)
Assumption	Market delimitation Affected suppliers	Inaccurate when market is not very local or well-known	Micro level	(Buyle *et al.*, 2014)
Linear regression	Market trend Affected supplier	Development can follow an S-shaped curve, not linear Trade and production data often used only as a proxy for competitiveness	Micro level	(Buyle *et al.*, 2018b, 2019b)
Iterative procedure	Market delimitation Market trend Affected suppliers	Production data as only a proxy for competitiveness Production and trade data are often aggregated at country level	Micro level	(Buyle *et al.*, 2018b, 2019b)
Network analysis (bottom-up)	Market delimitation market trend affected suppliers	Countries as affected suppliers; large countries may have considerable internal market variations	Micro level	(Sacchi, 2017)
Network analysis (top-down)	Market delimitation Market trend Affected suppliers	Trade data as the only measure for countries belonging to a network (market) Complimented/validated with qualitative information regarding studied products Market trend and affected suppliers' identification is less advanced	Micro and meso/macro level	(Pizzol and Scotti, 2017)
Electricity equilibrium models	Market delimitation Market trend Affected suppliers	Input data of weather data, installed renewable capacity, baseload, coal share of fossil fuels	Meso/macro level	(Roux *et al.*, 2017; Collinge *et al.*, 2018)
Economic equilibrium models	Market delimitation Market trend Affected suppliers	Choice or assumptions of input elasticities	Meso/macro level	(Nepal *et al.*, 2016)
MFA	Market trend	Omit resource price and availability relationship Exclude demand from other sectors for the same resource	Meso/macro level	(Cordier *et al.*, 2019)
Equilibrium and forest empirical model	Market delimitation Market trend Affected suppliers	Price elasticity assumptions from literature notably influence outcomes The base year of timber-use per unit and logging slash amount End of life options not considered	Meso/macro level	(Nepal *et al.*, 2016)

Many studies rarely employ all CLCA aspects, nor is the modelling process clearly specified. This could be upgraded to enhance the general consequential level of the cause-effect relationship (Roos and Ahlgren, 2018). Fauzi et al. (2021) studied various CLCA aspects with alternating specification levels. They discuss what affects a market in general, though the modelling of market delimitation is disregarded. They explain thoroughly what determines market trend and affected suppliers, while avoiding direct modelling by referring to the literature and ecoinvent, which can lead to internal inconsistency. The consequential ecoinvent database might lead to inconsistencies when used as the reference for the consequential changes in a foreground system in cases where the geographical aggregation is not representative of the given study. Further, they reason for and reference to constraints for one affected supplier but not for the remaining foreground processes. It is complemented by specifying the recycling rates of the substitution processes that nonetheless lack the detailed explanation behind their identification. The number of included CLCA aspects in the reviewed studies increased towards 2019 to an average of 5.4 of 6 CLCA aspects (see Fig. 1 in Supplementary Material). The range of CLCI modelling methods underlines the lack of consistency across studies and internally. Thus, the LCA community in the built environment could agree on a harmonized CLCI modelling method to increase the consistency of CLCAs. Adequate CLCA aspect applications should follow Table 5. A few studies include all CLCA aspects, explain determining parameters, and discuss the constraints of applying retrospective and prospective data (Nepal *et al.*, 2016; Buyle *et al.*, 2019b).

Substitution can appear as a market-based mechanism if it considers the substituted processes as the affected processes. Yet, the categorization might not be a purely consequential element due to the ILCD Handbook. ISO 14040 (2008), and ISO 14044 (2008) argue it can be used for attributional LCA and other types of LCA, respectively (attributional and consequential are not terms in the ISO standards). Several studies only include substitution alongside the time horizon, and disregard other market-based CLCI modelling. These nine studies are therefore semi-consequential, as defined by Zamagni et al. (2012). Turk et al. (2015) explain substitution in terms of which processes are avoided due to recycling using literature references, although not adequately specifying whether it involves the actual affected (marginal) processes, which makes the substitution aspect less causally market-based. The remaining LCI is not consequential as the modelling originates from the associated supply chain and not the affected supply chain in the market. Similarly, Sandin et al. (2013) performed a consequential LCA model, which neglected the identification of marginal suppliers except for including substitution to model avoided production by the unconstrained suppliers. Proceeding substitution onwards in CLCA of buildings, studies should model avoided processes to be the affected suppliers while also completing consequential modelling of the remaining foreground system to ensure a more useful CLCA study.

4.3 Application and guide of CLCA on buildings

The ILCD Handbook specifies to use ALCA for accounting and micro level decision support. For meso/macro level decision support, it specifies to combine the use of long-term marginal mixes for the large-scale changes and attributional modelling for the small-scale changes. However, it shows some ambiguity across chapters regarding when to apply attributional and consequential approaches, as elaborated in Section 1.1. Despite the ambiguity, it is a consensus document we recommend as the basis for the decision of which LCA approach to use. To condense the interpretation for the built environment, Table 4 provides a proposed guide of when ALCA and CLCA are relevant. Supplementary to the guide proposals, the micro level of decision support would benefit of an added CLCA, but not suggested as a requirement.

However, a dilemma arises for micro level decision support if a trend for a certain building or product type increases or decreases "independently" in each commenced building project. These individual micro level trends may amount collectively to a macro level change. It is important for consultants to recognize this. But, completing the CLCA jointly with the ALCA to improve the conclusions of such trends is mainly recommended for the building authorities and researchers. To make it easier to differentiate between micro or meso/macro level decision support of an LCA, the built environment community could agree on and introduce a distinctive threshold. This could, for example, built on the most appropriate of either total building area or total building project cost. We recommend initiative joint consensus work to establish clear criteria or recommendations for defining when a study is at the micro, meso or macro level.

Table 4 Relevancy guide of when to use which LCA approach at which decision support level

Decision Support Level	*Approach*	*Relevancy*	*Comments*
Micro level	ALCA	Building level projects of new, renovation, transformation, and material producers of less market-dominant positions	Based on ILCD 'Chapter 6.5' One building project may have a limited influence on the overall economy.
Meso/macro level	CLCA	Policy-making, regulation, and building development in neighbourhood, city, national, or regional context	Based on ILCD 'Chapter 5'; cf. section 1.1 It will reflect the causal market aspects of changes in the economy

Table 5. Minimum aspects to include in building CLCAs as derived from the four-step procedure framework of Weidema et al. (2009). Then, recommendations of what to include as a part of the assessment and a minimum specified level of documentation with examples

Aspect	*Recommendation (optionally)*	*Specification Level*
Time Horizon	Long-term (medium-, short-term)	No. of considered years, or as long-, medium-, and/or short-term
Market Delimitation	Modelled for foreground system	Explaining the parameters that determine the market, e.g., trade data and minimum threshold for being included in a certain market
Market Trend	Modelled for foreground system	Explaining the parameters that determine market trends, e.g., increasing market computed based on linear regressions of trade data
Affected Suppliers	Modelled for foreground system	Explaining parameters that determine affected suppliers e.g., trade data as a proxy for competitiveness and as a threshold for being in the affected supplier mix
Constrained Supply	Exclude qualitatively before or after modelling (quantitatively)	Discuss if affected suppliers are plausible and include a comparison with other literature, policies, or expert involvement
Substitution of Affected Processes	Multifunctional processes, recycling/reuse	Explaining the parameters that determine avoided production, e.g., avoided chipboard production from increased timber use for CLT.

After the choice to conduct a CLCA, instead of following the ILCD Handbook, it might act according to the four-step procedural framework of Weidema et al. (2009), where Table 5 presents the minimum level of the CLCA aspects we recommend for inclusion. The four-step framework provides an inherent homogeneous approach to CLCA, and of the 24 reviewed studies referring to a CLCA framework, 19 use the four-step framework or its predecessor's work and theories (Weidema *et al.*, 1999; Weidema, 2003; Ekvall and Weidema, 2004).

Regarding data application, retrospective and prospective data considerably influence the environmental impacts of building CLCAs (Buyle *et al.*, 2018b, 2019b, 2019a). Therefore, considering retrospective and prospective data on market delimitation, market trend and affected suppliers in a sensitivity analysis could be a common element in future CLCA studies of buildings. This improves the robustness of outcomes since retrospective data are often more available. However, they are not necessarily representative of future trends, whereas prospective data are inherently uncertain but can consider future changes due to their projection aspect (Pizzol and Scotti, 2017). Using scenario development to demonstrate various paths of future possibilities should reduce the inherent uncertainty of a prospective approach (Zamagni *et al.*, 2012). Developing robust scenarios requires a structured methodological framework, as in Pesonen et al. (2000). For ALCA studies, various scenario applications exist (Lasvaux *et al.*, 2017; Drouilles *et al.*, 2019; Scherz *et al.*, 2022).

5. Conclusion

This review has revealed how limited numbers of CLCA studies of buildings exist. The analysis shows a lack of methodological studies about the influence of CLCI modelling choices. Additional research gaps concern renovation approaches and the effects of future climate change pathways on CLCA outcomes. Micro level studies feature circular aspects and wood in buildings as their main subjects. The meso/macro level studies report on similar topics, though with geographically concentrated circular aspects, and accompanied by a focus on energy supply pathways. Ergo, wider circular strategies and renovation policies lack focus at the meso/macro level, while the premises of component design, material strategies and building configurations need stressing at both decision support levels. Although studies engage a broad spectrum of applications of both methodological and empirical aspects, the documentation and modelling methods of CLCI lack systematization and differ in consistency. Altogether, there is a need for further CLCA studies on buildings to provide a more comprehensive basis for concluding and generalizing outcomes. Studies also need to improve the level of CLCI to augment the quality of, and strengthen, the consequential approach and interpretations.

The choice of LCA approach was discussed with reference to the ILCD Handbook. It concluded that ALCA should be applied in micro level decision support, but that an additional CLCA may improve the insights into decision support because the ILCD Handbook suggests that the consequences of small-scale changes should be examined. This entails that building LCAs could continuously be conducted with the current standardized LCA for micro level studies. Building LCAs for meso/macro level decision support should as a minimum conduct it as a CLCA. The approach to conduct a CLCA may follow the four-step framework of Weidema et al. (2009) because it is homogeneous and the most frequently applied framework in the reviewed studies.

Meso/macro level decisions would primarily comprise policy-making, and building projects on a neighbourhood, city, national or regional scale involving policymakers, -advisors, and building development professionals. Micro level decisions would often be relevant for designers, advisors, and clients in individual building projects. It was proposed to agree on a threshold definition that simplifies the micro- and meso/macro level distinctions, for example, those characterized by the most appropriate measure of the size of the total building area or the total costs of the building project.

Appropriate CLCI modelling should be transparently documented and balance the decision support level, applicability and level of advancement while accommodating some element of the market approach. It ensures a more market mechanism-based assessment that captures constrained suppliers and creates the hypothetical affected supply chain. These are the principal elements from which CLCA deviates from ALCA. In any case, these CLCI aspects fluctuate in consistency and specification. Evolving consequential studies of buildings, we advocate the built environment agreeing on a CLCI modelling method to harmonize CLCA of buildings. Lastly, retrospective, or prospective data notably influence the environmental impacts of CLCA of buildings and should preferably be included as a sensitivity analysis.

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Declarations

Conflict of interest. The authors declare no competing interests.

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